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Spectral ageing: a new *age* perspective

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Abstract. We present an up-to-date critique of the physical basis for the spectral ageing method. We find that the number of cases where this method may be meaningfully applied to deduce the ages of classical double radio sources is small indeed. This critique is much more than merely a re-expression of anxieties about the calibration of spectral ageing (which have been articulated by others in the past).

1. One key observational point

Many people (e.g. Winter et al. 1980, Myers & Spangler 1985, Alexander & Leahy 1987) have observed that spectral indices change along the lobes of classical double radio galaxies. The general trend observed is that the lobe spectra are flatter in the outermost regions near the hotspot and steeper in the regions nearer the core. Often the observed change in spectral index, or the spectral gradient, is steady and systematic.

1.1. Two *a priori* interpretations

It is not widely acknowledged that there are in principle two physical interpretations of this behaviour. The traditional interpretation of spectral gradients goes as follows: the radiating electrons nearer the core were dumped by the hotspot much earlier in the past than the radiating electrons near the hotspot now, and so the former will have undergone greater synchrotron cooling compared with the latter. A radiating population whose energy distribution is initially a power-law, which suffered only synchrotron losses, would show a 'break' in this power-law at later times. This break frequency moves to lower frequencies as more time elapses (Kardashev 1962, Pacholczyk 1970, Jaffe & Perola 1973) predicting steeper measured spectral indices for the older emission. Thus far, there is consistency with observations. But an alternative physical picture explains the observations just as well: a gradient in magnetic field along the lobe together with a curved energy electron spectrum will result in a spectral gradient being observed along the lobe (see Fig. 1). Indeed, Rudnick, Katz-Stone and Anderson's (1994) analysis of multi-frequency images of Cygnus A show no evidence for any variation in the shape of $N(\gamma)$ across different regions of the lobe.

Without considering the underlying physics more deeply, one *cannot* distinguish between these two possibilities. So we now examine in turn the individual and collective assumptions which go into these two pictures.

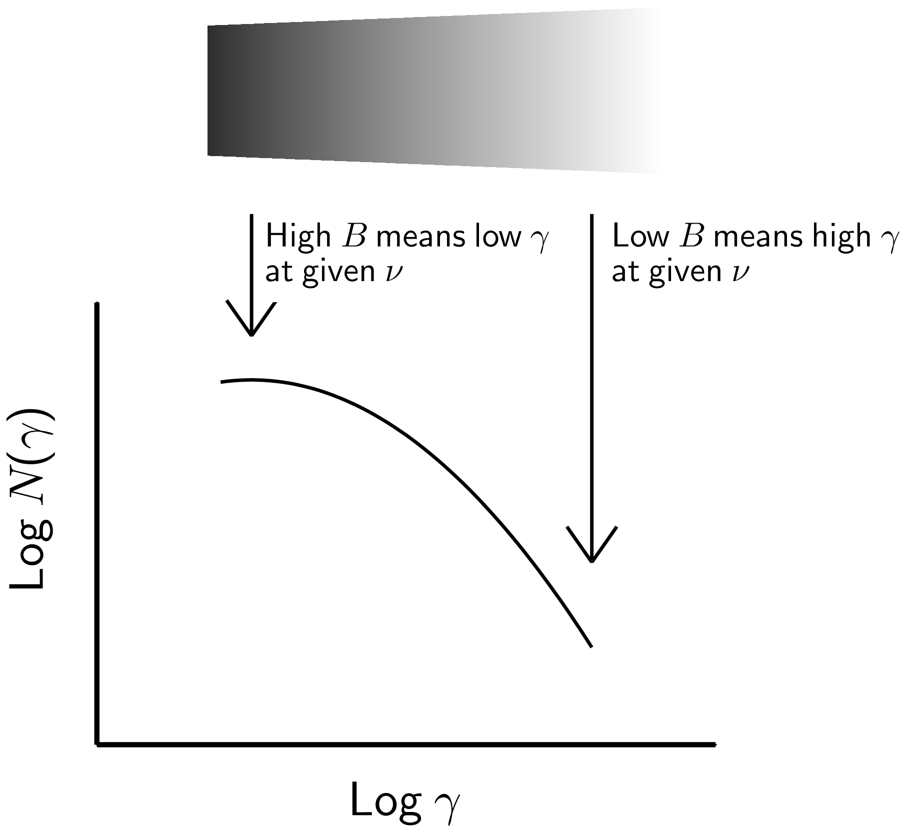

Figure 1. Illustration of how, when one observes a particular frequency ν across the lobe, the combination of a gradient in magnetic field together with a curved electron energy distribution $N(\gamma)$ will inevitably lead to a gradient in spectral index α ($\equiv \partial \log S_\nu / \partial \log \nu$).

2. Assumptions and predictions of the spectral ageing method

The spectral ageing method usually makes the following assumptions: i) the magnetic field strength is constant, ii) each segment or slice of lobe may be regarded as a discrete element of plasma and there is no mixing between the slices, iii) the radiative lifetimes of the synchrotron particles in the plasma are significantly longer than the spectral ages to be measured, and iv) the element of plasma being considered initially has a power-law distribution in energy.

A 'break-frequency' $\nu_{\rm B}$ in this power-law distribution is therefore deemed to evolve with time according to the following formula:

$$\nu_{\rm B} \propto \frac{1}{B^3 t^2} \tag{1}$$

where B is the magnetic field strength within the element of plasma and t is the time which has elapsed since the energy distribution was accelerated to its deemed power-law distribution. Sometimes this expression is slightly modified to incorporate the effects of the equivalent magnetic field due to inverse Compton scattering off the cosmic microwave background.

2.1. Spectral ageing assumption I: constancy of the magnetic field

The magnetic field strength at the time of observation is tricky to calibrate: an equipartition field strength has been frequently used in the spectral ageing methods in the past and such a value for the magnetic field strength appears to be correct within a factor of a few (Leahy, these proceedings).

The relationship between the local magnetic field strength B and the frequency ν at which most of the energy from particles with Lorentz factor γ will be radiated is given by:

$$\gamma^2 \propto \frac{\nu}{B}. \tag{2}$$

Thus, when one considers a particular fixed frequency (e.g. 151 MHz in the rest frame) observations of sources with *lower* magnetic field strengths will be from synchrotron particles with *higher* Lorentz factors, which are typically from a steeper part of the underlying energy spectrum.

A recent finding casts considerable doubt on the appropriateness of assuming that the synchrotron cooling has taken place in a constant magnetic field strength. Sources with larger physical sizes have steeper spectra[1] (Blundell, Rawlings and Willott 1999). This indicates that more expanded sources have lower magnetic field strengths. Consistently with simple physical pictures of the expansion of radio lobes (Blundell & Rawlings 2000) this indicates that the magnetic field decreases as the lobe expands sideways, as the age of the radio galaxy increases.

[1] as evaluated at 151 MHz in the rest frame, hence largely uncontaminated by core and hotspot emission, and indeed in the frequency regime whose spectral shape is alleged to be unaffected in the spectral ageing model, see Fig. 2.

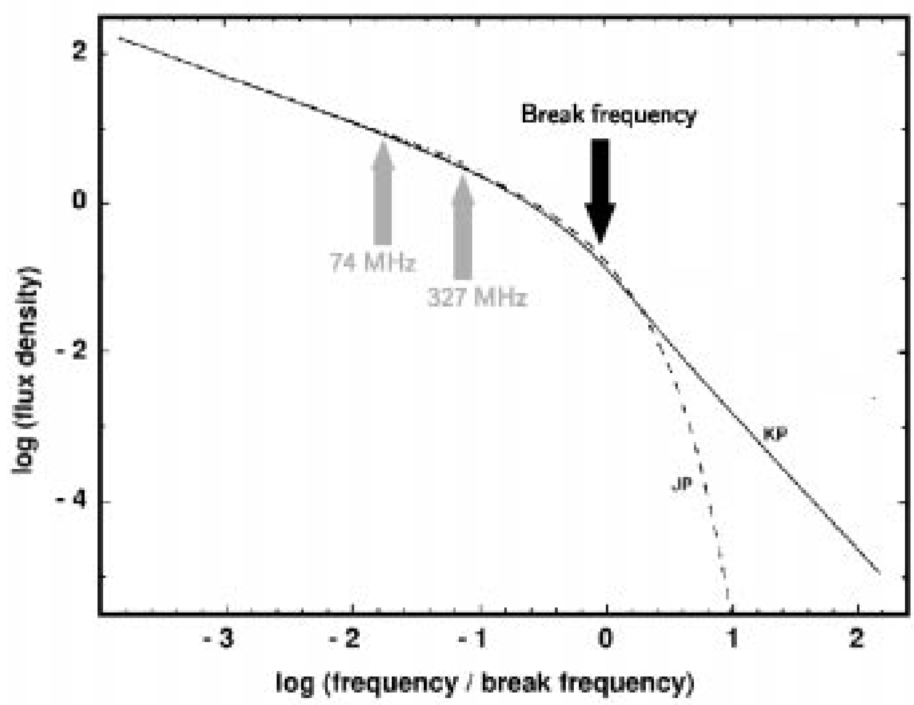

Figure 2. The solid curves are the predicted spectral shapes for two different models of synchrotron cooling [one with pitch-angle scattering (Jaffe & Perola 1973) and one without (Kardashev 1962 and Pacholczyk 1970)]. The large black arrow indicates the 'break–frequency' for these two models. Carilli et al (1991) fit the break frequencies along the lobes of Cygnus A to be $> 5\,\mathrm{GHz}$ independent of which of the two models is used. Taking the break frequency to be at the lower end of their measurements i.e. 5 GHz, we plot the frequencies of 74 MHz and 330 MHz. Inconsistently with the above picture, between these frequencies a spectral index gradient is actually observed. This beckons an alternative physical picture to that assumed in the spectral ageing method, see Fig. 1.

2.2. Spectral ageing assumption II: no mixing of populations

We now consider spectral ageing input assumption II. Jones, Ryu and Engel (1999) pointed out that any mixing of particles within the lobes will contaminate spectral ageing estimates. Possible origins of mixing include: bulk backflow and turbulent backflow as well as a variety of diffusion mechanisms. Which of these is the most effective transport mechanism depends on the details of the magnetic field configuration within the lobe; assuming a diffusion rate of zero is perhaps taking a liberty.

2.3. Spectral ageing assumption III: input/hotspot spectra are power-laws

We now consider spectral ageing input assumption III that the initial injection index is a straight power-law. State-of-the-art observations of hotspots over a wide frequency baseline show that their spectra are *curved* (see e.g. Carilli et al. 1991). Since the hotspots are believed to supply plasma into the lobes, it is hard to see how a curved input spectrum would be able to straighten itself out once in the lobe.

Moreover, the observed low-frequency asymptote is inconsistent with that assumed in the spectral ageing method: spectral gradients are observed well below the break frequencies in some lobes (see Fig. 2). The new 74 MHz receiver system on the VLA has enabled spatially resolved images at super-metre wavelengths for the first time. The spectral gradient in Cygnus A between 74 MHz and 330 MHz first published by Kassim et al (1996), shows a clear spectral gradient at frequencies well below the break frequencies fitted by Carilli et al (1991). This appears to be unexceptional behaviour for classical double radio galaxies (Perley et al. in preparation). This behaviour would not be observed if the spectral shape at these frequencies were power-laws. This observation is more consistent with assuming that there is a magnetic field gradient along the lobe.

2.4. Spectral ageing assumption IV: the radiative lifetimes are long enough

The spectral ageing model (e.g. Fig. 2) assumes that the radiative lifetimes of the synchrotron emitting particles (or the 'cooling times') are longer than the ages which are to be deduced. Matthews and Scheuer (1990) were the first to consider the evolution of the energies of the synchrotron particles, rather than the more commonly used evolution of the frequency spectrum. Their expression gives $\mathrm{d}\gamma/\mathrm{d}t$ if both synchrotron and adiabatic expansion losses are occurring:

$$-\frac{\mathrm{d}\gamma}{\mathrm{d}t} = \frac{2}{3}\sigma_{\mathrm{T}} m c \mu_0 \gamma^2 b^2 + \frac{\gamma}{R}\frac{\mathrm{d}R}{\mathrm{d}t}. \tag{3}$$

A similar relation, which includes inverse Compton losses off the cosmic microwave background, is given by Kaiser, Dennett-Thorpe and Alexander (1997).

If we consider some particular observing frequency, we can define a maximum time Δt which can elapse between an initial time t_{min} when a particle is injected into the lobe with a particular Lorentz factor γ and the time of observation if the particle is to emit synchrotron radiation at the *specified observing frequency* at the time of observation. This Δt can then be compared with the

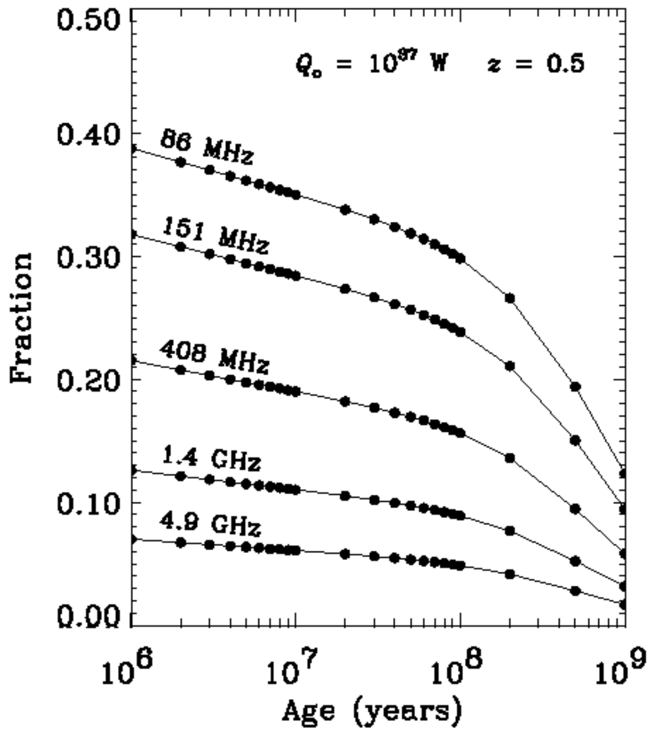

Figure 3. This plot shows the fraction of the age of the radio source for which the particles radiating at a certain frequency have been in the radio lobe, against the age of the radio-source. The bulk kinetic jet-power in the model source shown in this plot is 10^{37} W (for details of the assumed environment see Blundell & Rawlings 2000.) In this model the magnetic field gently decreases with time as the lobes expand. Even at low frequencies (< 200 MHz) the synchrotron lifetime of the radiating particles is significantly shorter than the current age of the source.

age of the radio source. Prior to this time $t_{\rm min}$, even if particles of extremely high Lorentz factor are injected into the lobe, their enhanced energy losses will be so catastrophic that their Lorentz factors will be too low at the time of observation[2] ($t_{\rm obs}$) to contribute to radiation at the given frequency, in a given B-field.

Thus for the ensemble of particles contributing to the radiation at a given emitted frequency at $t_{\rm obs}$, those which had the largest Lorentz factors at injection are injected at $t_{\rm min}$ and those with the lowest are those actually injected at $t_{\rm obs}$. There is no trivial identity which connects $t_{\rm min}$ with the age of the source, as Fig. 3 shows.

[2]We use the term 'time of observation' quite liberally here to mean 'when the source is intercepted by our light-cone' or 'when the light we ultimately observe leaves the source'.

2.5. Prediction of spectral ageing I

A prediction of spectral ageing is that the derived spectral ages should be consistent with the dynamical ages. The simplest constraints on source ages come from the measured projected physical size of an object and estimating the speed at which it has expanded to that size. The dimensional model of Falle (1991) has that the expansion speed of a radio galaxy *decreases* as the source gets *older* (in a given environment), so although proper motion measurements with VLBI techniques show that the smallest double radio sources appear to expand at $\sim 0.2\,c$ (Owsianik & Conway 1998, Owsianik, Conway and Polatidis 1998) this does not much constrain the expansion speeds of the large classical double radio sources. A more promising constraint comes from considerations of lobe-length asymmetries based on light-travel time arguments. These arguments benefit considerably from knowing which lobe is the nearer to us. Peter Scheuer, to whose memory this volume is dedicated, in 1995 used the presence of a jet in FR II quasars to infer speeds of $< 0.05c$. Arshakian (these proceedings) inferred slightly larger velocities for a somewhat different sample of FR II radio galaxies and quasars. Scheuer's speeds imply ages which are typically an order of magnitude larger than the spectral ages (Alexander & Leahy 1987).

2.6. Prediction of spectral ageing II

It was pointed out a number of decades ago (Jenkins & Scheuer 1976) that *if* synchrotron cooling played a part in the spectral shape of extended lobes, then the lobes should be more extended at lower frequencies. This rarely appears to be the case. For example, the observations by Leahy, Muxlow & Stephens (1989) of some 3C sources at 151 MHz with MERLIN and the VLA at 1.4 GHz show that the lobe lengths at these different frequencies are the same. (The flux-density measured by MERLIN is consistent with that measured by low-resolution instruments.)

2.7. Prediction of spectral ageing III

If the assumptions used in the spectral ageing model were correct, then there should be many more relic radio galaxies observed, i.e. there should be no prohibition on seeing hotspot-less, core-less lobes in the low-frequency sky. Such relic radio galaxies are however very rare with only a very few examples known (e.g. Cordey 1987). This strongly indicates that the radiative lifetimes of synchrotron particles in the lobes are not the three orders of magnitude larger than those of particles in hotspots required by the spectral ageing method.

3. Conclusion

The traditional way of interpreting observed gradients in spectral index along the radio lobes is the simple spectral ageing picture; we find that the assumptions which underlie this model, both individually and collectively, are flawed.

A combination of a gradient in magnetic field (which is physically plausible) together with a curved distribution in electron energy (which is measured) produces the same observed behaviour. In addition, this second model explains not just the observed spectral gradients *above* the break frequency but also those *below* the break frequencies.

References

Alexander, P. & Leahy, J.P., 1987, 'Ageing and speeds in a representative sample of 21 classical double radio sources', MNRAS, 225, 1-26

Blundell, K.M. & Rawlings, S., 2000, 'The spectra and energies of classical double radio lobes', AJ, 119, 1111-1122

Blundell, K.M., Rawlings, S. & Willott, C.J., 1999, 'The nature and evolution of classical double radio sources from complete samples', AJ, 117, 667-706

Carilli, C.L., Perley, R.A., Dreher, J.W., & Leahy, J.P., 1991, 'Multifrequency radio observations of Cygnus A — spectral aging in powerful radio galaxies', ApJ, 383, 554-573

Cordey, R.A., 1987, 'IC 2476 - A possible relic radio galaxy', MNRAS, 227, 695-700

Falle, S.A.E.G., 1991, 'Self-similar jets', MNRAS, 250, 581-596

Jenkins, C.R. & Scheuer, P.A.G., 1976, 'What docks the tails of radio source components?', MNRAS, 174, 327-333

Jones, T.W., Ryu, D. & Engel, A., 1999, 'Simulating electron transport and synchrotron emission in radio galaxies: shock acceleration and synchrotron aging in axisymmetric flows', ApJ, 512, 105-124

Kaiser, C.R., Dennett-Thorpe, J., & Alexander, P., 1997, 'Evolutionary tracks of FRII sources through the P-D diagram', MNRAS, 292, 723-732

Kardashev, N.S., 1962, 'Nonstationariness of spectra of young sources of non-thermal radio emission', SvA, 6, 317-327

Kassim, N.E., Perley, R.A., Carilli, C.L., Harris, D.E. & Erickson, W.C., 1996, 'Low frequency observations of Cygnus A', in 'Cygnus A – Study of a radio galaxy', 182-190, eds C.L. Carilli & D.E. Harris

Leahy, J.P., Muxlow, T.W.B., & Stephens, P.W., 1989, '151-MHz and 1.5-GHz observations of bridges in powerful extragalactic radio sources', MNRAS, 239, 401-440

Matthews, A.P. & Scheuer, P.A.G., 1990, 'Models of radio galaxies with tangled magnetic fields. I – calculation of magnetic field transport, Stokes parameters and synchrotron losses', MNRAS, 242, 616-635

Myers, S.T. & Spangler, S.R., 1985, 'Synchrotron aging in the lobes of luminous radio galaxies', ApJ, 291, 52-62

Owsianik, I. & Conway, J.E., 1998, 'First detection of hotspot advance in a Compact Symmetric Object. Evidence for a class of very young extragalactic radio sources', A&A, 337, 69-79

Owsianik, I., Conway, J.E. & Polatidis, A.G., 1998, 'Renewed radio activity of age 370 years in the extragalactic source 0108+388', A&A, 336, L37-L40

Pacholczyk, A.G., 1970, 'Radio Astrophysics', pub. W. H. Freeman & Co

Jaffe, W.J. & Perola, G.C. 1973, 'Dynamical models of tailed radio sources in clusters of galaxies', A&A, 26, 423–435

Rudnick, L., Katz-Stone, D.M. & Anderson, M.C., 1994, 'Do relativistic electrons either gain or lose energy, outside of extragalactic nuclei?', ApJS, 90, 955–958

Scheuer, P.A.G., 1995, 'Lobe Asymmetry and the Expansion Speeds of Radio Sources', MNRAS, 277, 331–340

Winter, A.J.B., Wilson, D.M.A., Warner, P.J., Waldram, E.M., Routledge, D., Nicol, A.T., Boysen, R.C., Bly, D.W.J. & Baldwin, J.E., 1980, 'The structure of Cygnus A at 150 MHz', MNRAS, 192, 931–944